

Is MBSE Helping?

Measuring Value on NASA's Europa Clipper Mission

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- Background and Context
- The Five System Engineering Challenges
- Introduction to Europa Clipper
- Europa MBSE Scorecard
- Conclusion
- Further information

Background and Context



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- JPL's Integrated Model Centric Engineering Initiative (IMCE)
 - 2009: IMCE Initiative established
 - First IMCE workshop focused on ConOps.
 - Key action: determine what problems MBSE is intended to address
 - Action answered by white paper "Articulating the Need"
 - Based on review of lessons learned from recent JPL missions.
 - Introduced the "Five System Engineering Challenges" (later included in INCOSE Vision 2025)
 - 2012: Augmented white paper to describe explicitly how MBSE could help address SE Challenges
 - This is the basis for a practical method for measuring value added by MBSE
- Europa Clipper
 - 2010: Europa mission study team, during early formulation phase, partnered with IMCE to attempt a concerted adoption of MBSE.
 - 2011: Study team delivered first modeling results (Mass List) on Europa Mission
 - 2014: Europa Clipper Pre-Project Team began Phase A after a highly successful MCR
 - 2017: Europa Clipper Project Team began Phase B after a highly successful SRR/MDR
 - This is a good point on the project to apply the value measurement technique

This paper proposes a value measurement method and applies it Europa Clipper

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- 1. Mission complexity is growing faster than our ability to manage it ...increasing mission risk from inadequate specification & incomplete verification
- 2. System design emerges from the pieces, not from an architecture ...resulting in systems which are brittle, difficult to test, and complex and expensive to operate.
- 3. Knowledge and investment are lost at project lifecycle phase boundaries ...increasing development cost and risk of late discovery of design problems.
- 4. Knowledge and investment are lost between projects ...increasing cost and risk; damping the potential for true product lines
- 5. Technical and programmatic sides of projects are poorly coupled ...hampering effective project decision-making; increasing development risk.

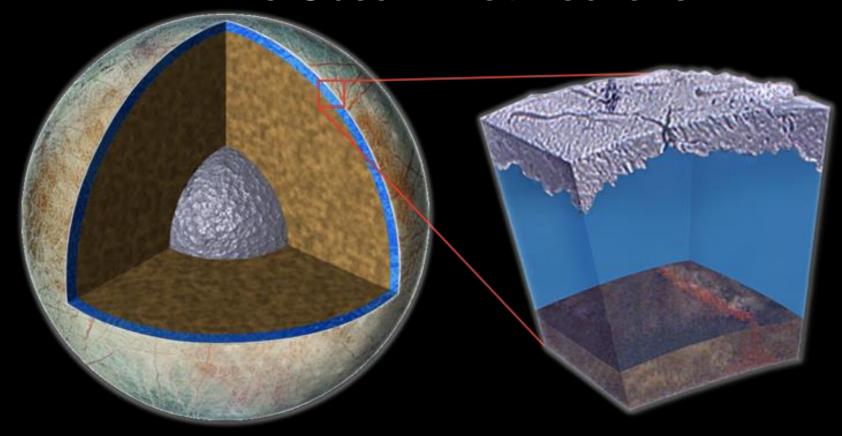
*JPL Internal IOM 3100-09-040, T Bayer, 24 Oct 2009



Intro to the planned Europa Mission



The Ocean That Beckons



"Europa, with its probable vast subsurface ocean sandwiched between a potentially active silicate interior and a highly dynamic surface ice shell, offers one of the most promising extraterrestrial habitable environments, and a plausible model for habitable environments beyond our solar system"

"Visions and Voyages", 2011 Planetary Decadal Survey



Europa: Ingredients for Life?

Water:

- Probable saltwater ocean, indicated by surface geology and magnetic field
- Possible lakes within the ice shell, produced by local melting

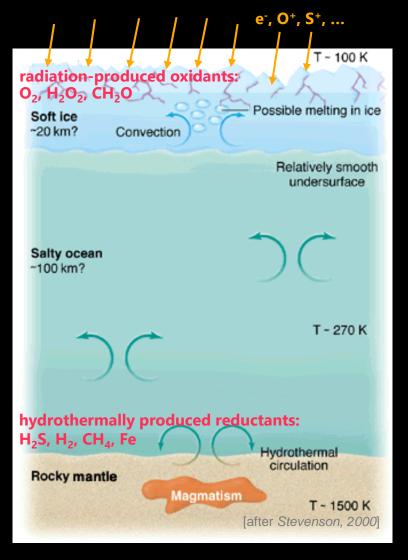
Chemistry:

- Ocean in direct contact with mantle rock, promoting chemical leaching
- Dark red surface materials contain salts, probably from the ocean

Energy:

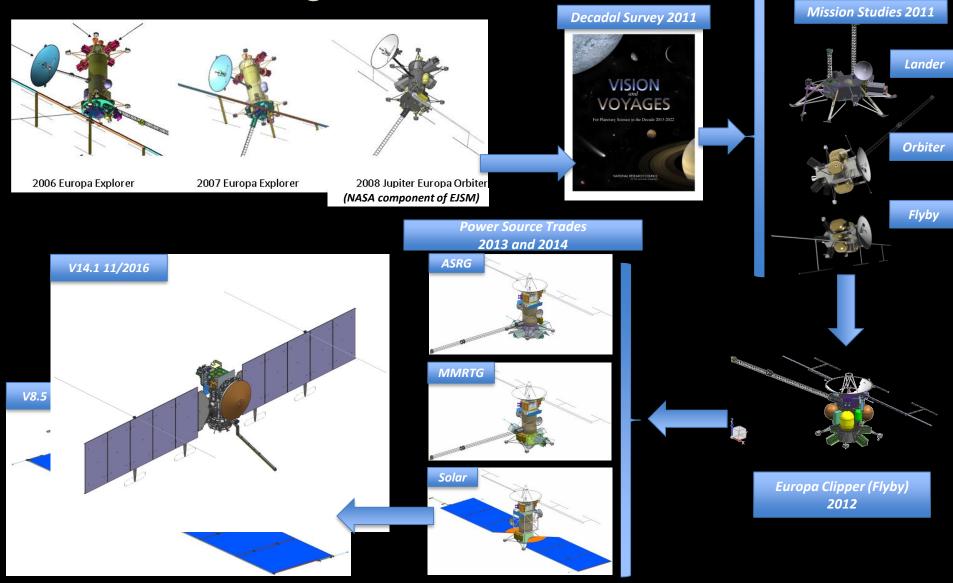
- Chemical energy could sustain life
 - Surface irradiation creates oxidants
 - Mantle tidal heating could create reductants
- Geological activity would "stir the pot"

The planned Europa mission would test habitability hypotheses

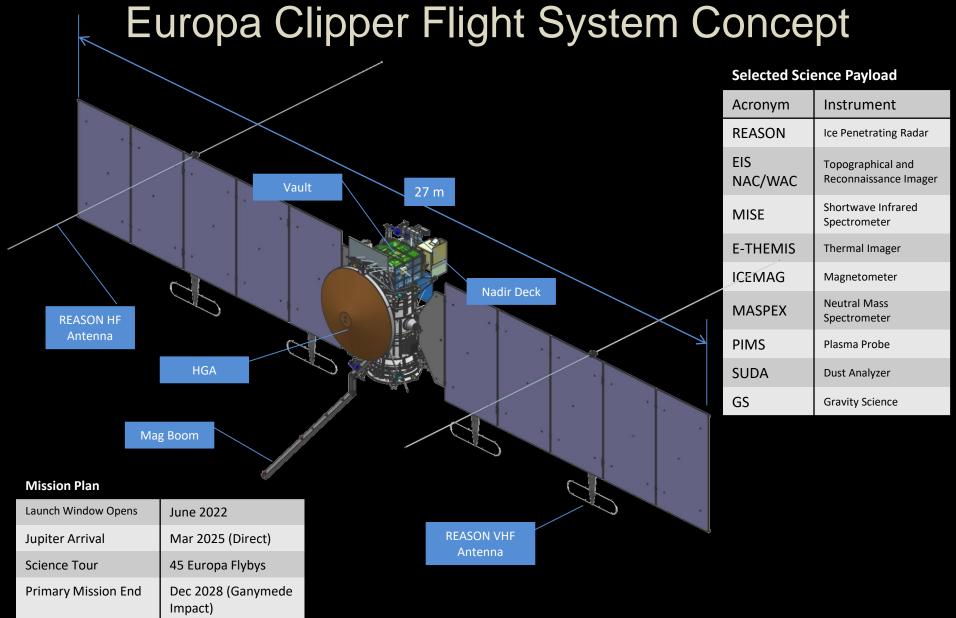




The long road to the current concept

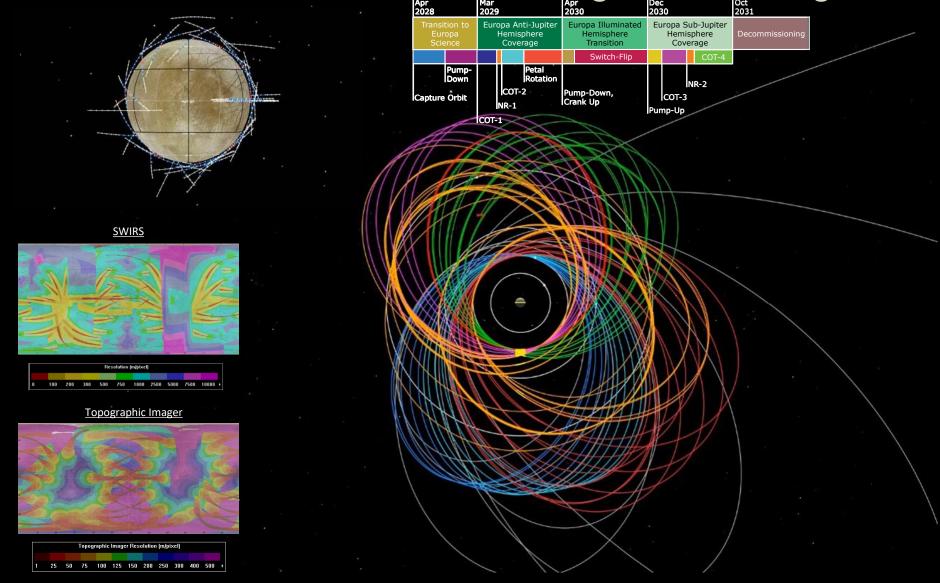






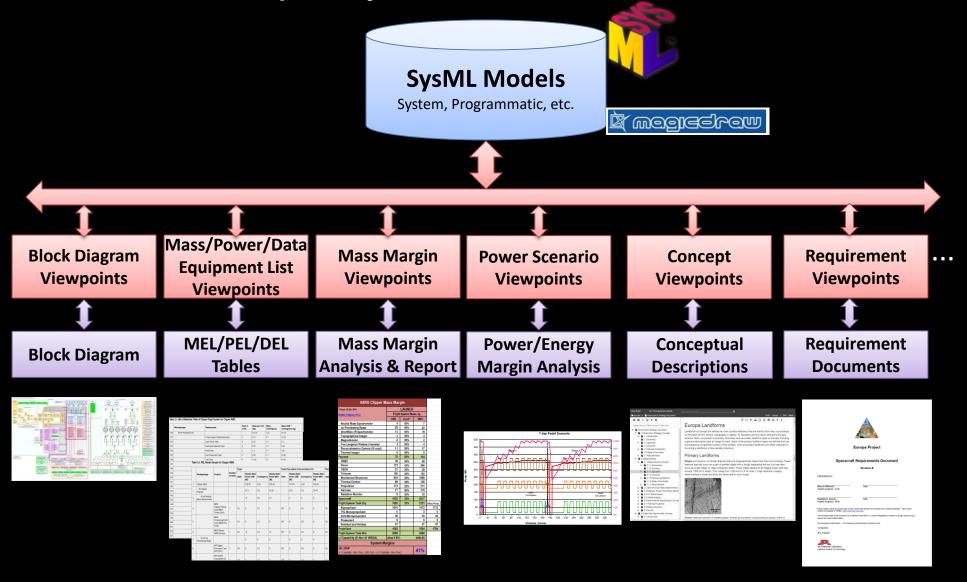


Innovative Mission Design is Enabling





Europa System Model Framework





MBSE Scorecard for the planned Europa Mission



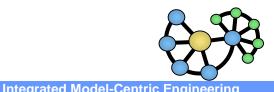


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Challenge 1: Growing Risk from Unmanag	ged Complexity	
	to manage it, increasing mission risk from inadequate specificati	ion & incomplete verification
Specific Issues	Envisioned Mitigations 2012	Europa Clipper Actual 2016
System behavior is often an emergent property	Enhanced understanding of system behavior and reasoning	FDDs with rigorous behavior diagrams allowed discovery of missing
discovered during system test	about engineering completeness	functions and requirements
Design errors are introduced through	Improved communication and reduced confusion using 'Single	System Model has saved time, prevented errors, minimized drudge work
miscommunication and go undetected until system	Source Of Truth' (SSOT) information	
test or even operations		
System properties are generated infrequently and at	Automatically generated human-interpretable documentation	Machine generated documentation provides monthly snapshots:
significant cost	provides frequent and authoritative snapshots of system	- System Model releases (MEL, PEL, block diagrams, system margins, etc)
	properties	- Concept Descriptions
		- Requirements Documents
		- Functional Description Documents
Design description comes together only infrequently,	Design reviews consist largely of model inspection and validation	Informal working level reviews often use model directly (MEL, PEL, '- Block
when preparing for major reviews		Diagrams, Modes, Scenarios, Requirements, Concepts, FDDs)
		MCR, and SRR/MDR were still hand-crafted powerpoint slide decks that tell
		a story BUT
		- more content came directly from system model, and
		- there were no major surprises in the review prep





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Challenge 2: System Design Emerges from the Pieces			
System design emerges from the pieces, rather than from an architected solution, resulting in systems which are brittle, difficult to test, and complex and expensive to operate.			
Specific Issues	Envisioned Mitigations 2012	Europa Clipper Actual 2016	
Architectural principles are seldom articulated or used	Having a better way to talk about our systems at an	- Explicit articulation and separation of concerns	
in design	architectural level enables us to do a better architecting job:	- Thorough, linked, living rationale for requirements	
	better separation of concerns; less unnecessary coupling; more	- Multiple constraints explicitly reconciled	
	coherence of function	- Analyses explicitly included in requirements flow	
		- Requirements explicitly associated with components	
System designs are spread across multiple	Design discussions between subsystems and with systems use	- SSOT for mass, power, composition, suppliers, interfaces, requirements.	
disconnected artifacts	common, authoritative representations	- System Model enables engineers to work and think at a higher level.	
		- System Modeling is a viable part of SE career path	
Domain physics-based models are not connected to	-Integrated models enable early validation of requirements	- Integration of high fidelity power model, sequencing planner, system	
each other or to a system model	completeness, operability, performance	model enabled full mission energy modeling (more examples to come!)	
	- Integration with physics-based models enables more complete	- System Model provides stable, repeatable inputs	
	design space exploration	- Better validation of System Model due to wide availability and use.	
Insufficient consideration of V&V during requirements	System model captures and encourages early V&V planning	A start: Requirements, components, functions explicitly associated.	
development		Phase B: integrate V&V events into system model	
Actual science merit of a given point solution is not	Architecture trades in formulation are informed by quantitative	- Science coverage of proposed Jovian tours (SIMPLEX)	
known until late	comparisons of science return	- Science data return with radiation upsets	
		- Gravity science modeling	
Desired system behaviors are poorly articulated,	System Behavior is specified rather than discovered:	A start.	
resulting in software whose behavior must be	- SE and SW collaborate on behavior models which are	- FDDs with explicit behavior diagrams	
'discovered'	executable/analyzable to discover logic flaws very early	- Power, Data Sims use scenarios in System Model	
	- FSW directly implements behavior models	- Phase B: make executable/autocodeable using SysML	
	Proposed design changes are expressed, analyzed, and	A start. System model impacts reported at Change Board, but model	

branch/merge is still being perfected

considered by change boards in the system model directly





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Challenge 3: Investments Lost at Phase Boundaries

Knowledge and investment are lost at project lifecycle phase boundaries, resulting in increased development cost and risk of delayed discovery of design problems.

Specific Issues	Envisioned Mitigations 2012	Europa Clipper Actual 2016
Formulation models are abandoned and new ones	System models evolve and mature from formulation through	- System Model has been used and evolved from Pre-Phase A through Phase
created when Implementation phase begins	operations	A and into Phase B.
	Rapid Mission Architecting and TeamX will eventually draw from	- Identical automated analyses have been applied to all configurations and
	the same line-developed model libraries as the implementation	versions, providing continuous history of concept evolution.
	team	
CM of existing models is lacking, impeding continued	Configuration management of the system design is rigorous, for	- Successfully configuration managed the mission concept Pre-Phase A and
use	the first time	Phase A.
		- This coupled with the iterative approach have allowed a concept to evolve
		in a controlled way.
		- Build up to major gate reviews is no longer the only time the baseline
		comes together. No major suprises at either gate review prep.
Essential attributes of design are not captured	Rich capture of design information is enabled: structure,	A start. Structure, behavior, requirements, delivery responsibility are linked.
consistently in readily accessible manner:	behavior, requirements, and parametrics connected in a unified	More linkage is possible
- Architectural principles	model	
- Trade study assumptions and rationale		
- System Design		
Training takes longer than necessary	- Model repositories enable quicker, more effective and less	- Vastly improved access to information for new team members. Rich
- Affects staffing arc during phases A-D	expensive training	system model allows self-study and exploration.
- Affects team turnover as projects moves into	- They also enable ongoing independent study and exploration	
operations		





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Knowledge and investment are lost between projects, increasing cost and risk, and damping the potential for true product lines.

Specific Issues	Envisioned Mitigations 2012	Europa Clipper Actual 2016
System architectures and designs are not well-	- Architecture and detailed designs are captured in a formalized	Within Clipper,
captured. Re-using them on subsequent projects is	and repeatable system model	- Enabled 5 major architectural variants to be analyzed in parallel in Pre
difficult and seldom happens except where the	- Once the architecture is captured, it is possible to consider	Phase A.
project team itself is 'inherited' by the next project	reusing all or part of it	- Enabled 3 full mission studies in the time it usually takes for 1 or 2
		Between projects:
		- Capabilities have been adapted for use in other projects with little
		additional effort (Clipper NRE is paying off): M2020, ARRM, others
		- Mission architectures have not yet been shared between projects. TBD in
		subsequent projects.
Too much of the system development "way of doing	- Increased reuse System Engineering Line Organizations join	- Line organizations have adopted and standardized mass and power models
business" is custom	Subsystem Line Organizations in curating libraries of CM'd and	and tooling
-tools (some)	reusable models, tools and processes.	- Line and Clipper are collaborating on additional standardized models -
-models (more)		behavior, electrical interfaces, etc.
-processes(much more)		





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Challenge 5: Poor Technical - Programmatic Coupling Technical and programmatic sides of projects are not well-coupled, hampering effective project decision-making and increasing development risk.		
Specific Issues	Envisioned Mitigations 2012	Europa Clipper Actual 2016
Cost, schedule, scope, investment, risk implications of	Behavioral, physical, cost and risk models are integrated	A start: System Model used as input to Phase A cost models for multiple
a given set of requirements, science objectives,	allowing for an integrated fully-informed approach to system	architecture variants, allowing more reliable and comparable cost model
components, functions is very difficult to determine.	optimization	results.
Trade studies seldom fully incorporate programmatic	Risk and resource implications of trade study options will be	A start: Model enables better trade choices: identical automated analyses
considerations. Existing tools do not support such a	better understood	are applied to all configurations and versions, providing more consistent,
view.		controllable generation of system metrics and normalization of risk
		assessment.



Future Work: Some improvements will first be apparent in future mission phases



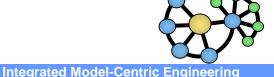
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Challenge 1: Growing Risk from Unmanaged Complexity		
Specific Issues	Envisioned Mitigations 2012	Europa Clipper Actual 2016
System test must cover full set of possible behaviors	System test activities focus on model validation and correlation	TBD in Phase D
- Mission Ops teams must work around unresolved	Fewer surprises and workarounds in operations.	TBD in Phase D/E
development issues		
- Significant in-flight anomalies can occur; some are		
mission-threatening		
Challenge 2: System Design Emerges from	the Pieces	
Specific Issues	Envisioned Mitigations 2012	Europa Clipper Actual 2016
	Kludges are less necessary and their impact more fully	A start. More reliable margins -> fewer resource "hunts" -> less future regret
	understood	from hasty decisions. TBD in Phase B/C/D
Where they exist, principles are abandoned to solve	Architectural principles are explicit and enforceable in the design	A start. Explicit association of requirements with system components is first
pressing technical problems		step to enabling performance assessment against requirements.
Desired system behaviors are poorly articulated,	Missions arrive at the launch pad with more of their architecture	TBD in Phase B/C/D
resulting in software whose behavior must be	intact, reducing operations cost and risk	
'discovered'		
	Integrated model at parameter level enables synoptic view and	TBD in Phase C/D
the system	minimizes chance of missed interactions	
Challenge 4: Insufficient Re-use of System Designs		
Specific Issues	Envisioned Mitigations 2012	Europa Clipper Actual 2016
Heritage reviews narrowly focus on full re-use of	Well-architected systems have less tightly coupled parts,	TBD in subsequent projects
components	enabling more reuse	
The current institutional guidance (e.g., JPL Design	Good architecture capture enables sharing of architecture and	TBD in subsequent projects
Principles), while providing important and useful	design principles between projects	
heuristics and lessons learned, is not sufficient to		
enable architecture re-use.	Copyright 2018 California Institute of Technology. US Government st	monsorship acknowledged.

Conclusion

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- Before embarking on Europa MBSE, it was extremely valuable to consider what problems could be solved and to envision what the end state might look like.
 - This guided the initial applications of MBSE and contributed significantly to their success.
- Europa has shown compelling benefits so far
- There is more work, and much more promise, in the years ahead
- We plan to check the scorecard at the end of subsequent phases

Further Information



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Integrated Model-Centric Engineering

For this work the joint Europa/JPL Integrated Model Centric Engineering Teams were awarded the NASA SE Excellence Award in 2013



https://nen.nasa.gov/web/se/announcements/-/announcements/detail/2070

Recent papers on Europa MBSE

- Update on the Model Based Systems Engineering on the Europa Mission Concept Study, IEEE Aerospace Conference Proceedings, 2013, Todd Bayer, Seung Chung, Bjorn Cole, Brian Cooke, Frank Dekens, Chris Delp, Ivair Gontijo, Dave Wagner.
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- Early Formulation Model-centric Engineering On Nasa's Europa Mission Concept Study, Proceedings of 22nd Annual International Symposium (IS2012), Rome, Italy, 2012, T. J. Bayer, S. Chung, B. Cole, B. Cook, F. Dekens, C. Delp, I. Gontijo, K. Lewis, M. Moshir, R. Rasmussen, and D. Wagner.
- Update Concept of Operations for Integrated Model-Centric Engineering at JPL, IEEE Aerospace Conference Proceedings, 2011, T. Bayer, M. Bennett, C. Delp, D. Dvorak, J. S. Jenkins, S. Mandutianu.
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